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PIPING VIBRATION EVALUATION SYSTEM

Report No 87-180-K

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ABSTRACT

A data acquisition and processing system based on an IBM-PC computer has been developed to evaluate piping vibration problems. An outline of the main features of this system together with examples of its application are presented to show how pressure and vibration measurements may be used to locate vibration sources.

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EXECUTIVE SUMMARY

PIPING VIBRATION EVALUATION SYSTEM

R.G. Ko
Plant Equipment Dynamics Section
Mechanical Research Department

This report describes an IBM-PC based system that has been developed for the evaluation of piping vibration problems based on pressure and vibration measurements. The quantities being determined include acoustic intensity in the flow and structural wave intensity in the piping structure, both useful for pin-pointing vibration sources.

Examples of its application are presented to verify basic principles and demonstrate its capabilities. It is shown that reliable pressure wave measurements and extrapolation to other locations depend on an accurate knowledge of sound speed which is very sensitive to local flow conditions. A "three-transducer" method is proposed in place of the usual "two-transducer" one in order to determine the sound speed. In one example, the relationship between acoustic velocity and vibration velocity at an elbow is verified. In another example, it is shown that the location of excitation input to a steel bar is indicated by the sign of the structural wave intensity. All of the demonstrated techniques are applicable to field vibration problems.

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TABLE OF CONTENTS

		Page
1	INTRODUCTION	1
2	OVERVIEW OF HARDWARE	1
3	OVERVIEW OF COMPUTER SOFTWARE	2
	3.1 ASYST	2
	3.2 DATA ACQUISITION AND BASIC PROCESSING	2
	3.3 FURTHER PROCESSING	3
4	APPLICATION EXAMPLES	3
	4.1 MEASUREMENTS AROUND AN ELBOW	3
	4.2 MEASUREMENTS AROUND A GLOBE VALVE AND A BUTTERFLY VALVE	4
	4.3 MEASUREMENT OF ACOUSTIC INTENSITY	4
	4.4 MEASUREMENT OF STRUCTURAL WAVE INTENSITY	5
5.0	CONCLUSIONS	5
REFERENCES		
FIGURES 1 TO 37		
APPENDIX A: FORMULATION FOR ACOUSTIC MEASUREMENTS		
APPENDIX B: FORMULATION FOR STRUCTURAL WAVE INTENSITY		
DISTRIBUTION		last page

LIST OF FIGURES

1. Piping vibration evaluation system
2. Programmable low-pass filter
3. Typical characteristics of a low-pass filter
4. Measurements around an elbow
5. Predicted pressure at elbow from upstream measurements in kPa, assuming c = 500 m/s
6. Predicted velocity at elbow from upstream measurements in kPa, assuming c = 500 m/s
7. Predicted pressure at elbow from downstream measurements in kPa, assuming c = 500 m/s
8. Predicted velocity at elbow from downstream measurements in kPa, assuming c = 500 m/s
9. Upstream velocity minus downstream velocity in kPa, assuming c = 500 m/s
10. Velocity of elbow in kPa times 1.4
11. Predicted pressure at elbow from upstream measurements in kPa, assuming c = 1600 m/s
12. Predicted pressure at elbow from downstream measurements in kPa, assuming c = 1600 m/s
13. Predicted pressure at elbow from upstream measurements in kPa, assuming c = 275 m/s
14. Predicted velocity at elbow from upstream measurements in kPa, assuming c = 275 m/s
15. Predicted pressure at elbow from downstream measurements in kPa, assuming c = 275 m/s
16. Predicted velocity at elbow from downstream measurements in kPa, assuming c = 275 m/s
17. Upstream velocity minus downstream velocity in kPa, assuming c = 275 m/s
18. Velocity of elbow in kPa times 1.4
19. Measurements around a globe valve and a butterfly valve
20. Actual pressure at location 5
21. Predicted pressure at location 5 based on downstream measurements
22. Actual pressure at location 6
23. Predicted pressure at location 6 based on downstream measurements
24. Actual pressure at location 7
25. Predicted pressure at location 7 based on upstream measurements
26. Acoustic intensity upstream of butterfly valve, .9 setting

27. Acoustic intensity downstream of butterfly valve, .9 setting

28. Acoustic intensity upstream of butterfly valve, .4 setting

29. Acoustic intensity downstream of butterfly valve, .4 setting

30. Acoustic intensity upstream of butterfly valve, .3 setting

31. Acoustic intensity downstream of butterfly valve, .3 setting

32. Set-up for measurement of structural wave intensity

33. Structural wave intensity from accelerometers 1 and 2

34. Structural wave intensity from accelerometers 1 and 3

35. Structural wave intensity from accelerometers 1 and 2, with ends of steel bar reversed

36. Structural wave intensity from accelerometers 1 and 3, with ends of steel bar reversed

37. Pressure waves at two measurement locations

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To Dr. D. Mills
Director of Research

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PIPING VIBRATION EVALUATION SYSTEM

1. INTRODUCTION

This report describes a piping vibration evaluation system that consists of an IBM-PC micro-computer, a DT2801A analog to digital board, a 32-channel low-pass anti-aliasing filter, transducers (accelerometers and pressure transducers) and a computer software package specially developed for the present purpose. The basic functions of this system are to acquire vibration data and process the data in a way that will point out the source of the vibration as well as the solution to the vibration problem.

The main advantages of this system are its relatively low cost, flexibility in adapting to new problems and specialization in techniques pertinent to piping systems. In particular, it will be shown in this report that the "three-transducer technique" is invaluable in locating the source of vibration and can be carried out conveniently with the present system. This technique, together with other evaluations to be detailed later, is not readily available with commercial systems.

The following sections give a general outline of the principles of measurement, the quantities being measured, and some interesting results. Computer programs will be discussed in general but will not be detailed. It will be seen that the results point out the importance of using the "three-transducer method" rather than the current "two-transducer" for water flow systems, and demonstrate the effects of turbulence on acoustic measurements. The emphasis of this report is on describing the capability of this system.

The present system has been applied to a New Brunswick Power vibration problem/1/, fundamental studies on the Feeder Pipe Loop (which are elaborated in this report), and the moderator piping vibration problem at Pickering NGS, Unit 8/2/. Development is continuing as knowledge and experience on vibration source identification improve with each application.

2. OVERVIEW OF HARDWARE

A diagrammatic description of the system is given in Figure 1. Transducers, either pressure or acceleration, provide the required signals which are amplified and/or integrated by signal conditioners, filtered to prevent aliasing, and then digitized by the A/D board. The filter consists of a total of 32 channels which were constructed from a circuit shown in Figure 2. The characteristics of a typical filter are shown in Figure 3. A steep roll-off is evident at the cut-off frequency.

The cut-off frequency is set by switches SW1 to SW6, as shown in the table in Figure 2. That table is based on a 1.0 MHz crystal in the circuit and the frequencies shown can be changed by changing the crystal. The actual cut-off frequency is selected to be at or slightly below the Nyquist frequency (which is half the sampling frequency for each channel).

The A/D board has 16 analog input channels. In order to handle up to 32 channels of signals, multiplexers controlled from the digital output of the A/D board are implemented into the filter. The alternating function of the computer to sample analog data and control the multiplexers, however, slows down the overall sampling rate of the system considerably.

The 20 Mbyte hard disc meets the minimum requirement to operate this system efficiently. Each data file, containing 320 time histories of 1024 data points, occupies 657 Kbytes of storage. An IBM-PC/AT works twice as fast as an XT when used to carry out a Fast Fourier transform and is therefore preferred. Also, an AT allows higher sampling speeds when used with the multiplexer. There is no difference in sampling speed when the number of channels is restricted to 16.

The A/D board has an external trigger input that can be used to synchronize data acquisition with externai events. Alternatively, the computer program provides the option of sampling Channel 13 continuously until a certain preset input voltage is detected, at which time data acquisition starts. This alternative is sometimes preferred when control of the sign and magnitude of triggering voltage is desired.

A dot matrix printer is used for producing hard copies of figures. A plotter is preferred to give better figures in less time. However, some changes in the computer programs are necessary to do that. The present set-up is more convenient because the printer is readily available.

3. OVERVIEW OF COMPUTER SOFTWARE

3.1 ASYST

Most of the programs for this work were developed based on a commercially available software package ASYST. A user-developed program consists of commands or "words" taken from the ASYST dictionary or defined by the user, and can be used to drive the A/D board and carry out FFT (Fast Fourier transform) or other functions. The drawback of carrying out FFT by software is the low speed, especially when an XT is used. The actual time to obtain a spectrum from 1024 data points is measured in seconds rather than milliseconds. The time factor can be important when averaging is required for a large number of input channels. This, however, has not been found to be a major problem in actual applications to date.

3.2 Data Acquisition and Basic Processing

Three groups of computer programs are used according to the number of analog input channels. When only a pair of transducers is used, such as in measuring structural wave intensity along a pipe wall, a program AI alone can be used to carry out most functions: acquisition, analysis, on-screen display of results and producing hard copies. Signals up to 4800 Hz can be handled. When the number of transducers is from 1 to 16, data acquisition is carried out by the program ACQDM16, the FFT is carried out by the program ANADM16 and the calculation of quantities like acoustic intensities and reflection coefficients is carried out by the program INTDM16. The maximum frequency of the input signals is limited to 610 Hz regardless of the type of computer. The corresponding programs for 17 to 32 analog input channels are ACQ32, ANA32 and INT32, and the maximum frequency is 38 or 73 Hz depending on whether an XT or AT is used. The results are saved in files that can be conveniently recalled for display or further processing.

Appendices A and B give definitions of the quantities that are calculated in basic processing.

3.3 Further Processing

Two programs are developed in this respect.

1) INF - This program allows detailed calculation and display of left- and right-running pressure waves based on results obtained from basic processing, and also enables extrapolation of the results to other locations. This program is used, for example, to correlate the pressure and acceleration measurements at an elbow in the example of Section 4.1.

2) EFF - From the response of a linear system to known excitations that are considered to be in the same directions and locations as the unknown excitations under operating condition, it is possible to estimate those unknown excitations using the program EFF. This program has been verified using electrical pink noise to simulate transducer signals and a linear system whose transfer matrix is simply the unit matrix. The practicality of this program in solving real problems will likely depend on how well the unknown excitations are represented in directions and locations, and the level of extraneous noise in the measurements.

4. APPLICATION EXAMPLES

Early applications of the present system were aimed at verifying some assumptions that are fundamental to evaluation techniques. Two such verifications are described below related to pressure waves in single phase flow. Another two applications, also described below, are to demonstrate the capabililty of the acoustic and structural wave intensity measurements in detecting the location of the source of excitation.

4.1 Measurements Around An Elbow

The elbow under investigation is part of the Feeder Pipe Loop in the Nuclear Process Components Test Facility. This elbow is located near the inlet of a centrifugal pump. A sketch of this elbow with measurement locations is given in Figure 4. A pair of pressure transducers, Nos 1 and 2, determines the acoustic pressure and velocity upstream of the elbow while another pair, Nos 3 and 4, is for downstream measurements. An accelerometer is mounted at the elbow with its sensing direction as shown in the figure. From theory, the acoustic pressure estimated at the elbow based on upstream measurements should match that of downstream measurements, while the difference in acoustic velocity immediately upstream and downstream of the elbow should be equal to $\sqrt{2}$ the velocity deduced from the acceleration measurement.

In verifying the above relations, the test data needs to be processed according to an assumed sound speed which is an unknown quantity. It is easily seen from existing literature that the sound speed in pure water varies from a maximum theoretical value of 1600 m/s to approximately 90 m/s at 2 per cent void fraction, and 50 m/s at 5 per cent void fraction. Due to the extreme sensitivity of sound speed to minute quantities of air or vapour bubbles, it is not feasible to verify the present techniques based on an assumed sound speed. Instead, a trial-and-error method is used in data processing to determine a value for the sound speed so that the acoustic pressure from upstream measurements matches that from downstream measurements in magnitude and phase. Based on this sound speed, the difference in acoustic velocities at the elbow is then compared with the velocity measurements by the accelerometer. The above measurements and comparisons were carried out with two loop operating conditions to detect any change in sound speed between tests.

Results for one test are shown in Figures 5 to 10 with an assumed sound speed of 500 m/s. It is seen that a sound speed of 500 m/s gives very good matching between the upstream and downstream predictions of acoustic pressure at the elbow, both in terms of magnitude and phase. The phase angles in all the figures are referred to the acoustic pressure at transducer No 1. From Figures 9 and 10, it is seen that the difference in acoustic velocities across the elbow agrees with the velocity of the elbow at or above 10 Hz. The magnitude is small because of low vibration of the elbow but the agreement in phase over the whole range of frequency is very good.

The same calculation, but with a sound speed of 1600 m/s, produces pressure predictions at the elbow shown in Figures 11 and 12. It is seen that there is a

mismatch in phase angle at high frequencies between the upstream and downstream predicted pressures.

Results for another test are shown in Figures 13 to 18. The flow in this test was approximately the same as in the previous test, but the temperature had gone up from 35 to 60 degrees C. It is seen in this case that a wave speed of 275 m/s gives again good correlation between the upstream and downstream pressures, and the velocity at the elbow. The drop in wave speed is probably due to the effect of temperature on dissolved air in the water or it may indicate that the amount of cavitation, if present, had increased at the higher temperature.

Since it is not possible to determine the wave speed from only two pressure transducers, it is evident that the only reliable way to measure pressure waves in a liquid system is to use at least three pressure transducers so that by matching the predictions from the upstream and downstream pair of transducers, an appropriate sound speed can be deduced.

4.2 Measurements Around a Globe Valve and Butterfly Valve

A pair of pressure transducers, Nos 5 and 6, provided pressure measurements between a globe valve and a butterfly valve as shown in Figure 19. Another pair, Nos 7 and 8, provided pressure measurements downstream of the butterfly valve. This part of piping is located upstream of the main flow resistance of the loop which comprises of sections of small diameter "feeder pipes" and a "fuel channel". Hence high static pressure and absence of cavitation are expected. For this test, both valves were fully open.

It is expected that due to the difference in construction of the two types of valves, the butterfly valve will not contribute turbulence and resistance to the flow whereas the globe valve will even when it is fully opened. Thus the acoustic measurements by the upstram pair of transducers will be mixed up with turbulent noises while the downstream pair will be relatively free of noises. The object of this test is to demonstrate the effect of turbulent noises on the accuracy of acoustic wave measurements by comparing the extrapolated upstream pressures at a downstream location to the actual downstream pressure, and vice versa.

Results are shown in Figures 20 to 25. It is clear that, using an assumed wave speed of 1600 m/s, downstream measurements can be reliably extrapolated to upstream locations. However, the extrapolation of upstream measurements to downstream locations is unsatisfactory, due to the effects of turbulence produced by the globe valve. These results point out that caution must be taken in locating pressure measurement points to avoid highly turbulent flow. They also point out that the sound speed can be close to the theoretical maximum limit under appropriate conditions (eg absence of bubbles and rigid pipe wall).

4.3 Measurement of Acoustic Intensity

Acoustic intensities were calculated based on the pressures from the pressure transducers described in Section 4.2. The measurements were carried out with the butterfly valve set at 0.9 (fully open), 0.4 and 0.3 (0.1 means fully closed). The aim of these tests was to examine how the butterfly valve behaved in terms of production and transmission of acoustic energy at various degrees of opening.

Results are shown in Figures 26 to 31. It is seen that:

1) When the valve is fully open, acoustic energy from upstream sources flows through the valve with little change. The valve itself, however, seems to absorb acoustic energy from a downstream source at around 14 Hz.

2) Most turbulence was generated at the valve setting of 0.4 as seen from the scatter of data in Figure 29.

3) The partial closure of the valve reduced the transmission of acoustic energy at low frequencies noticeably in either direction. However, the flow of acoustic energy at some higher frequencies such as 70 Hz was not affected.

The above tests demonstrate the usefulness of using the acoustic intensity method to determine the direction of the source of excitation.

4.4 Measurement of Structural Wave Intensity

Vibration energy can be transmitted along a structure in different forms such as bending waves along a beam, longitudinal elastic waves and torsional waves. The measurement in this demonstration is restricted to bending waves along a steel bar. Those waves can be readily picked up by a pair of accelerometers as shown in Figure 32. Here, an electromagnetic shaker with an input signal from a "pink noise generator" excited one end of the bar. A wooden board is clamped to the other end. Vibration energy is transmitted through the bar to the board which acts as an energy absorber. Three equally-spaced accelerometers are attached to the bar. The objective is to check for consistency among the intensities determined from any two accelerometers. Appendix B shows the formulation for the wave length of bending waves. Valid measurement of intensity requires that the spacing between a pair of accelerometers be much smaller than the wavelength. The measurements were repeated with the ends of the bar interchanged.

Results are shown in Figures 33 to 36. It is clear that:

1) The sign of the measured intensity changes when the ends are interchanged, demonstrating the ability of the present method to point out the direction of excitation.

2) When the spacing between accelerometers is large, the accuracy of the results suffers at the high frequency end of the spectrum (compare Figure 33 with 34 or 35 with 36) due to finite difference approximation. On the other hand, it is expected that a large spacing will improve the accuracy at the low frequency end.

5.0 CONCLUSIONS

This report describes a data acquisition and diagnostic system designed to investigate piping vibration problems. This system acquires and processes pressure signals to give acoustic intensity that indicates the strength and direction of acoustic sources. It also conditions the acceleration signals to give structural wave intensity that indicates where the energy is transmitted from the fluid to the structure.

The examples in this report, other than demonstrating various techniques, reveal some interesting features that deserve further attention. The most important feature is the sensitivity of the wave speed to local flow conditions. It is shown that the wave speed varied between 275 to 1600 m/s depending apparently on the amount of cavitation and presence of gas bubbles. It is shown that a "three-transducer" method should be used in place of the standard "two-transducer" method if variation of wave speed is a factor.

At present, this system is being applied to a piping vibration problem at Pickering NGS with apparent success in pin-pointing vibration sources. Further applications are planned. Further system development is also planned to facilitate diagnosis of field piping problems.

Approved:

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Submitted:

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4. D. Quinlan, "Adaptation of the Four Channel Technique to the Measurement of Power Flow in Structures", 2nd International Congress on Acoustic Intensity, CETIM, Sept 1985.

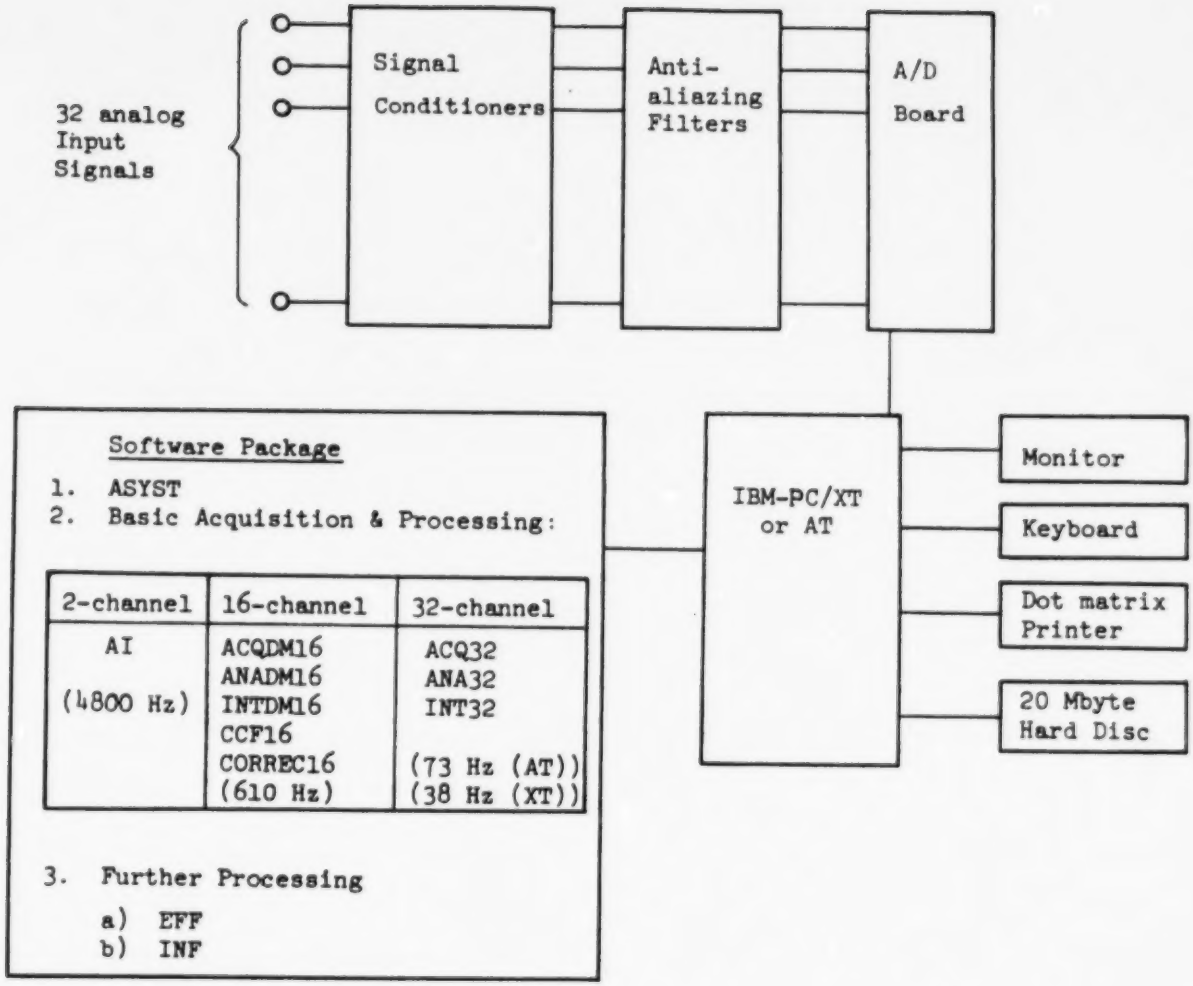
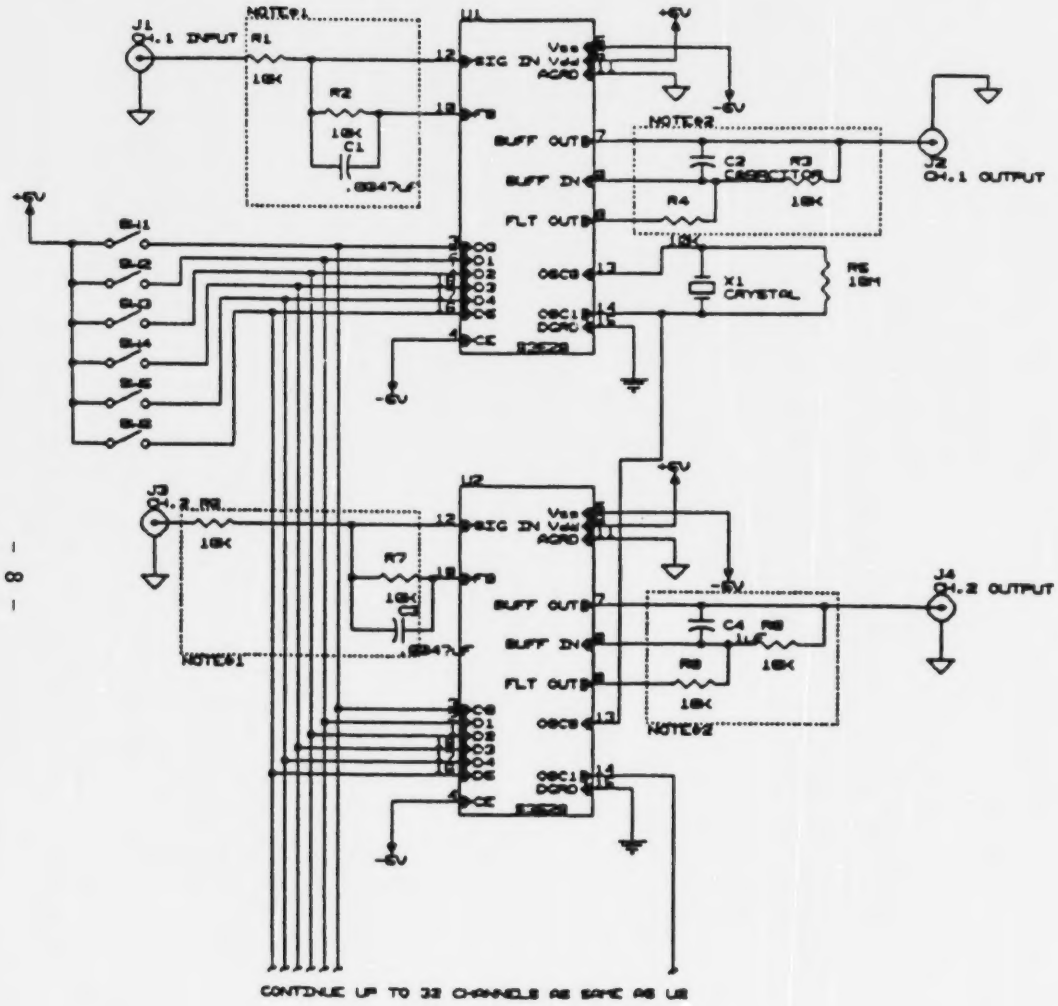


FIGURE 1
PIPING VIBRATION EVALUATION SYSTEM



STANDARD FREQUENCY TABLE: PROGRAMMABLE FILTER 83528

FCLOCK = 1.000M

INPUT CODE D5-D0	FC ACTUAL (HZ)	SW1 (D0)	SW2 (D1)	SW3 (D2)	SW4 (D3)	SW5 (D4)	SW6 (D5)
00	12.3	OFF	OFF	OFF	OFF	OFF	OFF
01	24.6	ON	OFF	OFF	OFF	OFF	OFF
02	36.9	OFF	ON	OFF	OFF	OFF	OFF
03	49.2	ON	ON	OFF	OFF	OFF	OFF
04	61.5	OFF	OFF	ON	OFF	OFF	OFF
05	73.8	ON	OFF	ON	OFF	OFF	OFF
06	86.1	OFF	ON	ON	OFF	OFF	OFF
07	98.4	ON	ON	ON	OFF	OFF	OFF
08	110.7	OFF	OFF	OFF	ON	OFF	OFF
09	123.0	ON	OFF	OFF	ON	OFF	OFF
0A	135.3	OFF	ON	OFF	ON	OFF	OFF
0B	147.6	ON	ON	OFF	ON	OFF	OFF
0C	159.9	OFF	OFF	ON	ON	OFF	OFF
0D	172.2	ON	OFF	ON	ON	OFF	OFF
0E	184.5	OFF	ON	ON	ON	OFF	OFF
0F	196.8	ON	ON	ON	ON	OFF	OFF
10	209.1	OFF	OFF	OFF	OFF	ON	OFF
11	221.4	ON	OFF	OFF	OFF	ON	OFF
12	233.7	OFF	ON	OFF	OFF	ON	OFF
13	246.0	ON	ON	OFF	OFF	ON	OFF
14	258.3	OFF	OFF	ON	OFF	ON	OFF
15	270.6	ON	OFF	ON	OFF	ON	OFF
16	282.9	OFF	ON	ON	OFF	ON	OFF
17	295.2	ON	ON	ON	OFF	ON	OFF
18	307.5	OFF	OFF	OFF	ON	ON	OFF
19	319.8	ON	OFF	OFF	ON	ON	OFF
1A	332.1	OFF	ON	OFF	ON	ON	OFF
1B	344.4	ON	ON	OFF	ON	ON	OFF
1C	356.7	OFF	OFF	ON	ON	ON	OFF
1D	369.0	ON	OFF	ON	ON	ON	OFF
1E	381.3	OFF	ON	ON	ON	ON	OFF
1F	393.6	ON	ON	ON	ON	ON	OFF
20	405.9	OFF	OFF	OFF	OFF	OFF	ON
21	418.2	ON	OFF	OFF	OFF	OFF	ON
22	430.5	OFF	ON	OFF	OFF	OFF	ON
23	442.8	ON	ON	OFF	OFF	OFF	ON
24	455.1	OFF	OFF	ON	OFF	OFF	ON
25	467.4	ON	OFF	ON	OFF	OFF	ON
26	479.7	OFF	ON	ON	OFF	OFF	ON
27	492.0	ON	ON	ON	OFF	OFF	ON
28	504.3	OFF	OFF	OFF	ON	OFF	ON
29	516.6	ON	OFF	OFF	ON	OFF	ON
2A	528.9	OFF	ON	OFF	ON	OFF	ON
2B	541.2	ON	ON	OFF	ON	OFF	ON
2C	553.5	OFF	OFF	ON	ON	OFF	ON
2D	565.8	ON	OFF	ON	ON	OFF	ON
2E	578.1	OFF	ON	ON	ON	OFF	ON
2F	590.4	ON	ON	ON	ON	OFF	ON
30	602.7	OFF	OFF	OFF	OFF	ON	ON
31	615.0	ON	OFF	OFF	OFF	ON	ON
32	627.3	OFF	ON	OFF	OFF	ON	ON
33	639.6	ON	ON	OFF	OFF	ON	ON
34	651.9	OFF	OFF	ON	OFF	ON	ON
35	664.2	ON	OFF	ON	OFF	ON	ON
36	676.5	OFF	ON	ON	OFF	ON	ON
37	688.8	ON	ON	ON	OFF	ON	ON
38	701.1	OFF	OFF	OFF	ON	ON	ON
39	713.4	ON	OFF	OFF	ON	ON	ON
3A	725.7	OFF	ON	OFF	ON	ON	ON
3B	738.0	ON	ON	OFF	ON	ON	ON
3C	750.3	OFF	OFF	ON	ON	ON	ON
3D	762.6	ON	OFF	ON	ON	ON	ON
3E	774.9	OFF	ON	ON	ON	ON	ON
3F	787.2	ON	ON	ON	ON	ON	ON

NOTE#1: ANTI-ALIASING FILTER
NOTE#2: SMOOTHING FILTER

FIGURE 2
PROGRAMMABLE LOW-PASS FILTER

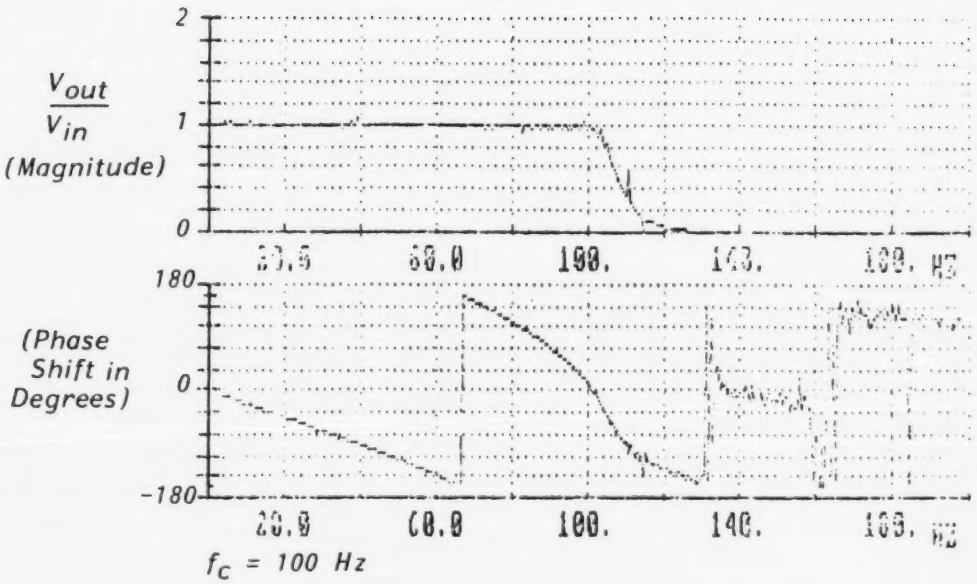


FIGURE 3
TYPICAL CHARACTERISTICS OF A LOW-PASS FILTER

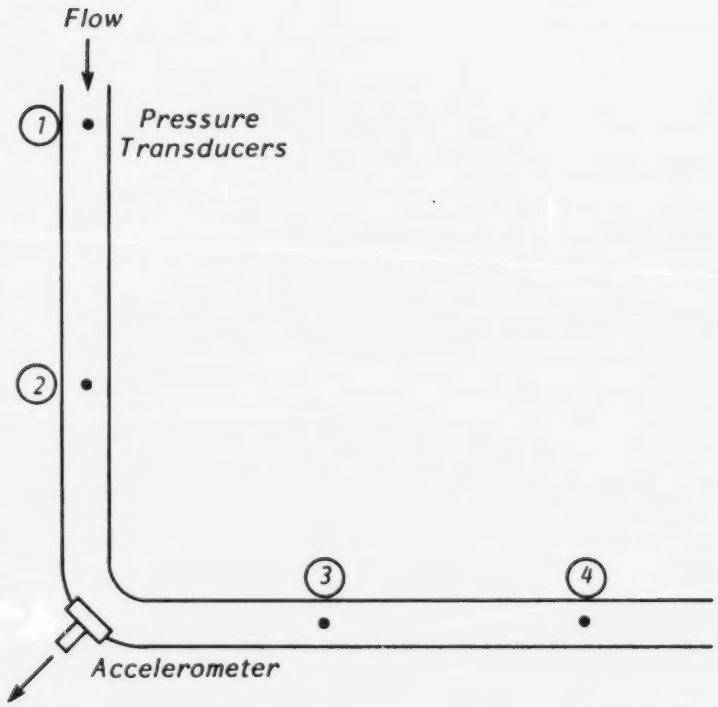


FIGURE 4
MEASUREMENTS AROUND AN ELBOW

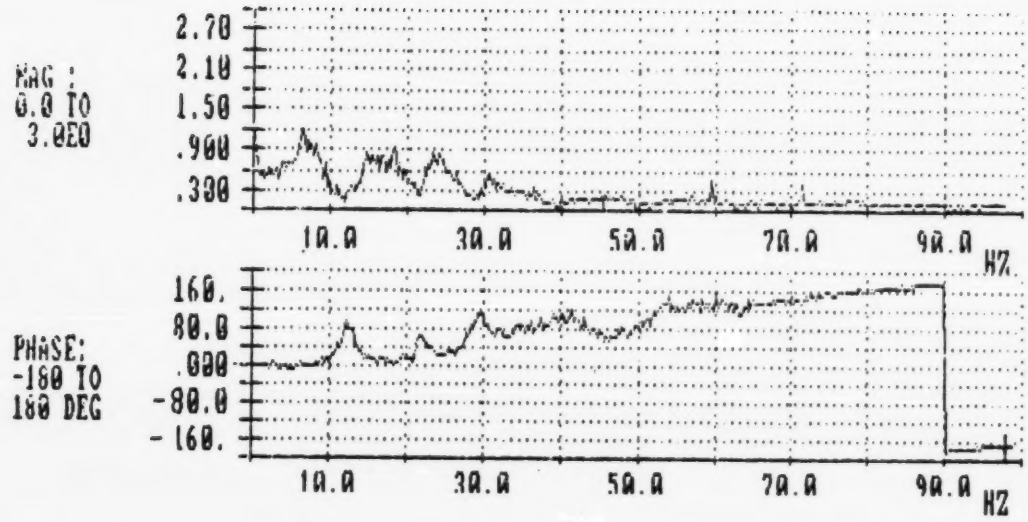


FIGURE 5

PREDICTED PRESSURE AT ELBOW FROM UPSTREAM MEASUREMENTS IN kPa, ASSUMING c = 500 m/s

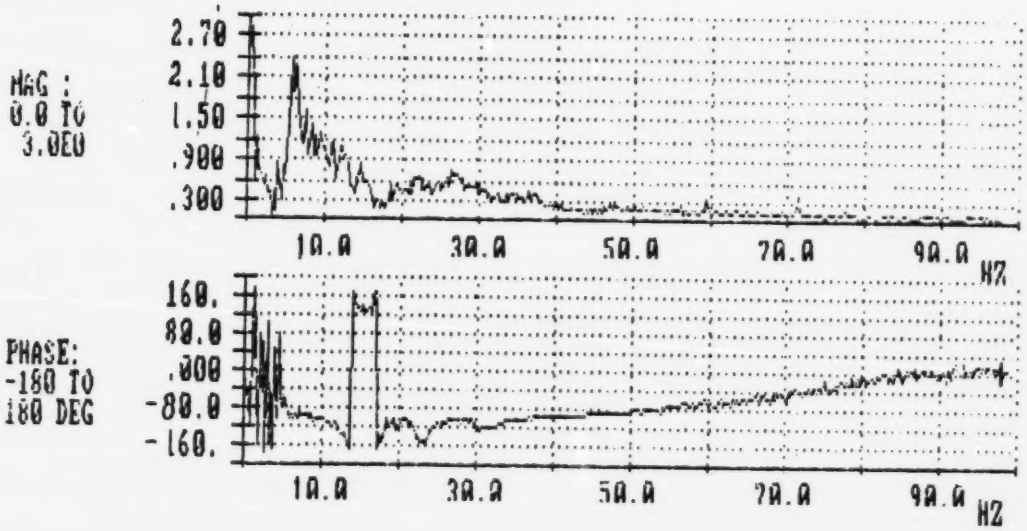


FIGURE 6

PREDICTED VELOCITY AT ELBOW FROM UPSTREAM MEASUREMENTS IN kPa, ASSUMING c = 500m/s

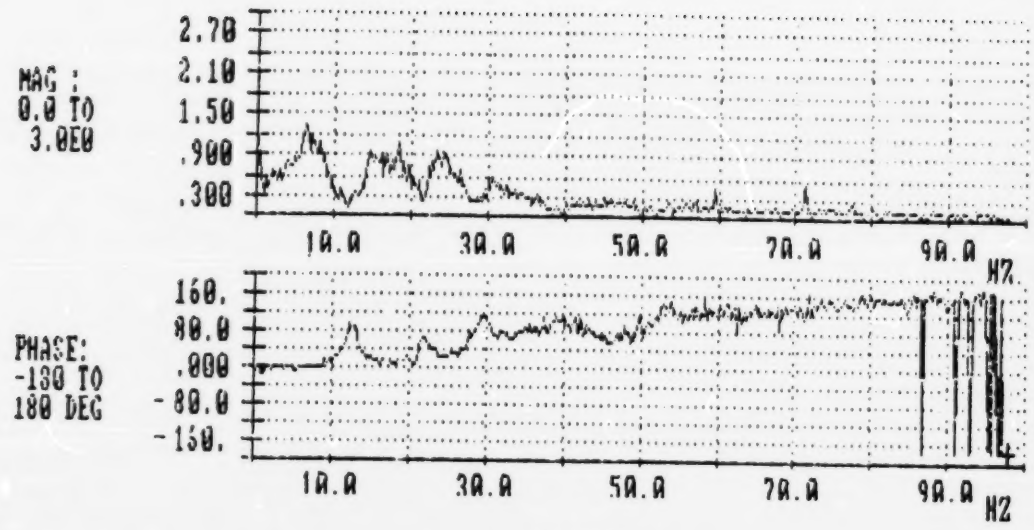


FIGURE 7

PREDICTED PRESSURE AT ELBOW FROM DOWNSTREAM MEASUREMENTS IN kPa, ASSUMING c = 500 m/s

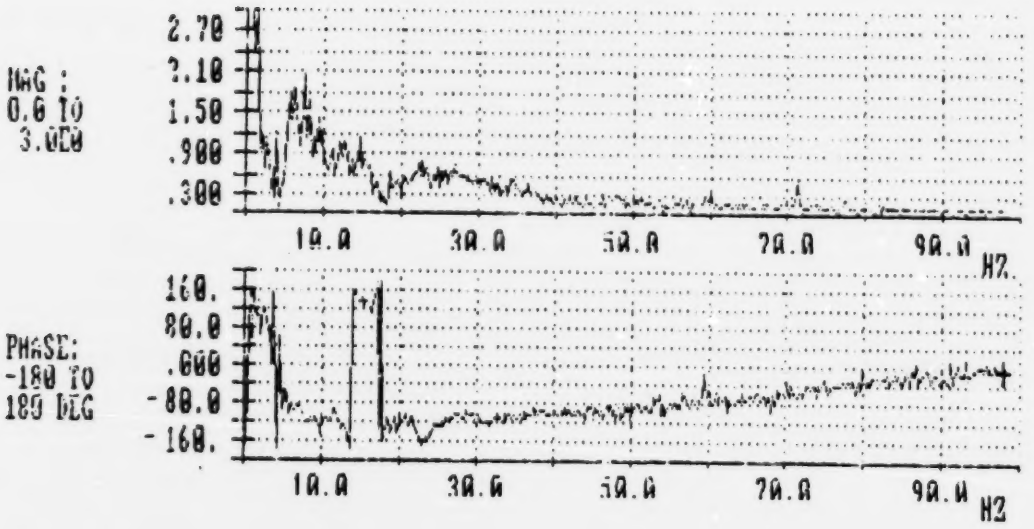


FIGURE 8

PREDICTED VELOCITY AT ELBOW FROM DOWNSTREAM MEASUREMENTS IN kPa, ASSUMING c = 500 m/s

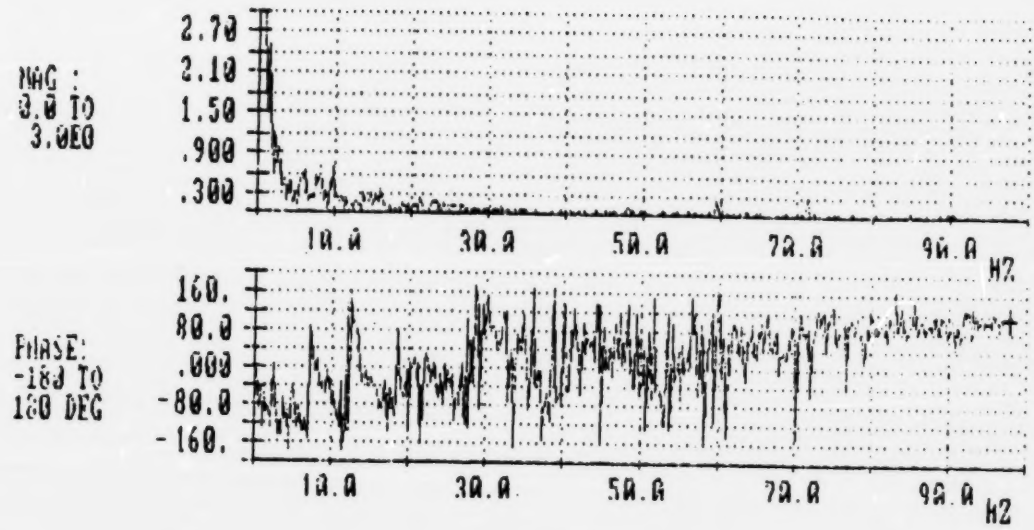


FIGURE 9

UPSTREAM VELOCITY MINUS DOWNSTREAM VELOCITY
IN kPa, ASSUMING c = 500 m/s

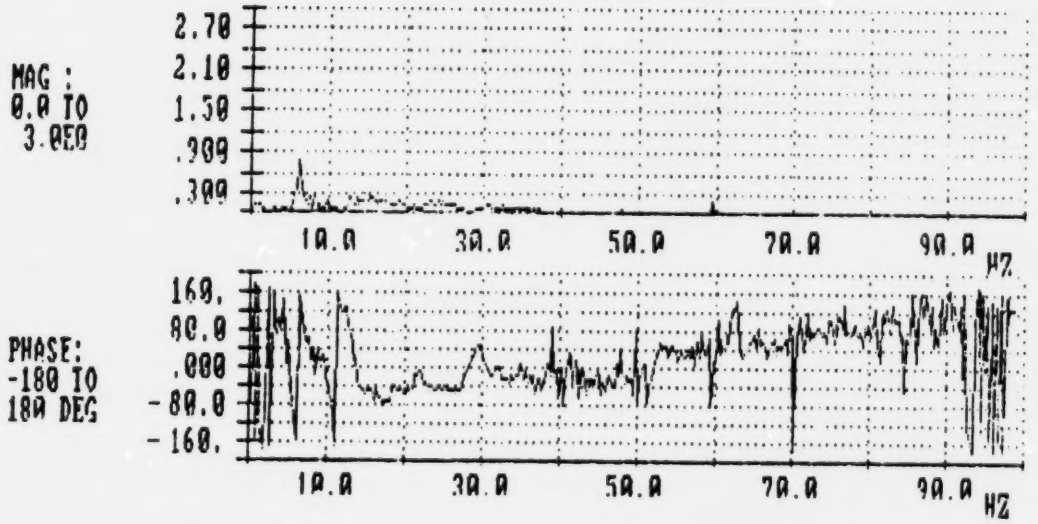


FIGURE 10

VELOCITY OF ELBOW IN kPa TIMES 1.4

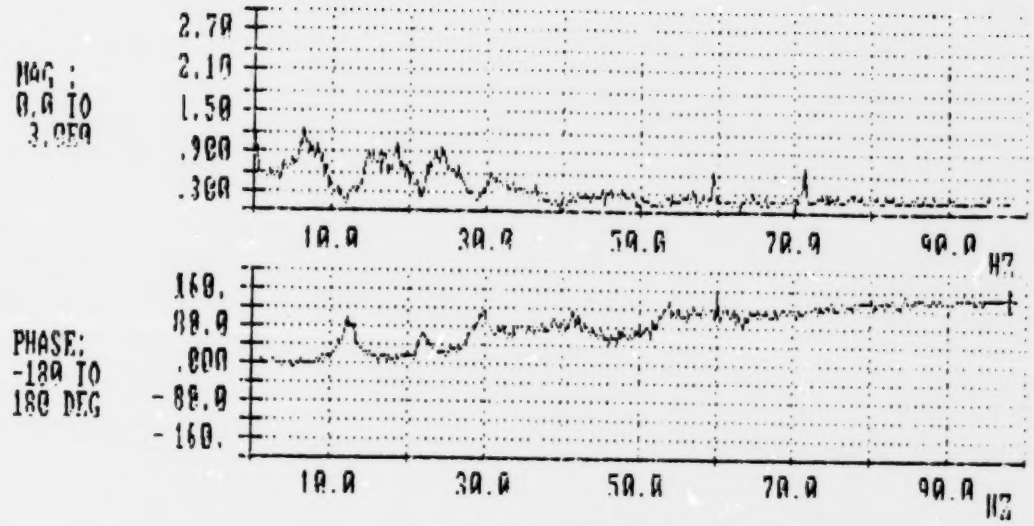


FIGURE 11

PREDICTED PRESSURE AT ELBOW FROM UPSTREAM MEASUREMENTS IN kPa, ASSUMING c = 1600 m/s

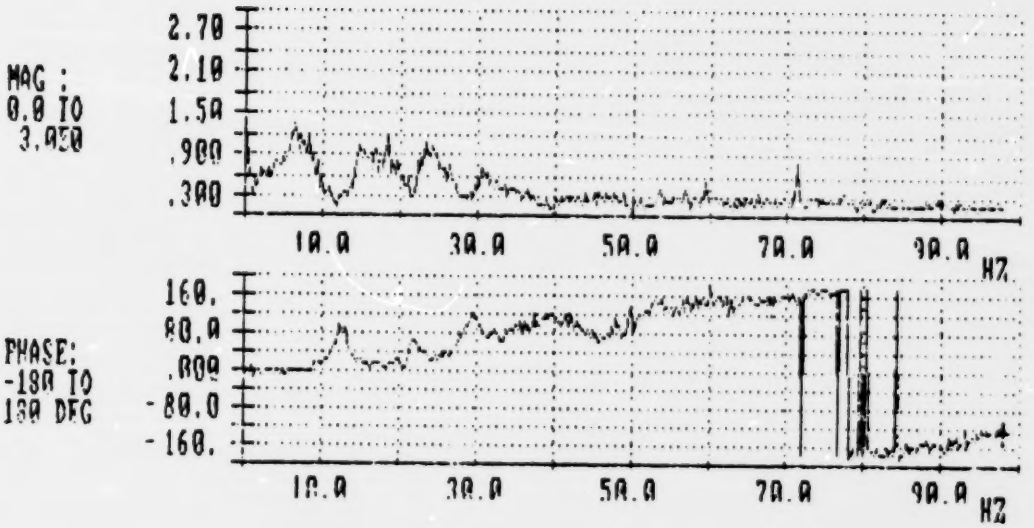


FIGURE 12

PREDICTED PRESSURE AT ELBOW FROM DOWNSTREAM MEASUREMENTS IN kPa, ASSUMING c = 1600 m/s

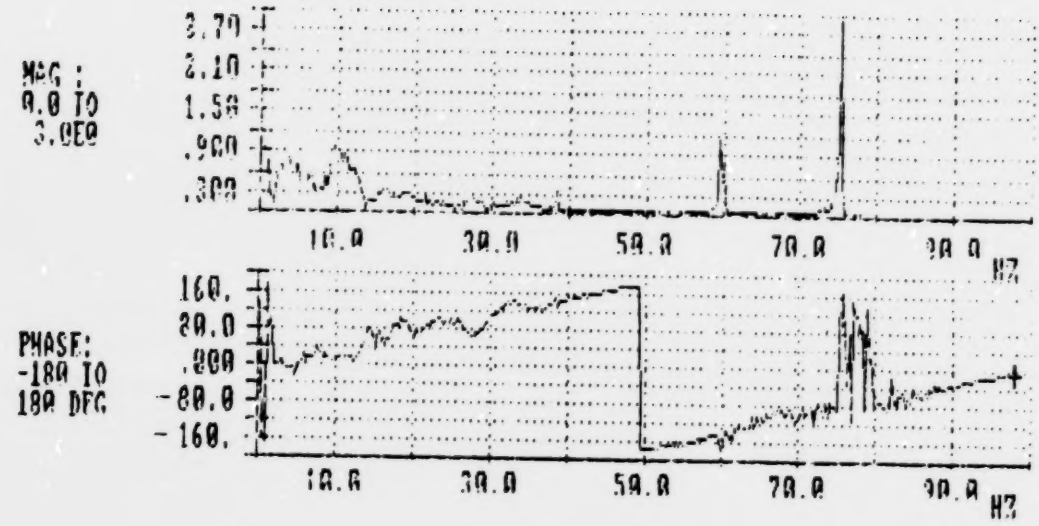


FIGURE 13

PREDICTED PRESSURE AT ELBOW FROM UPSTREAM MEASUREMENTS IN kPa, ASSUMING c = 275 m/s

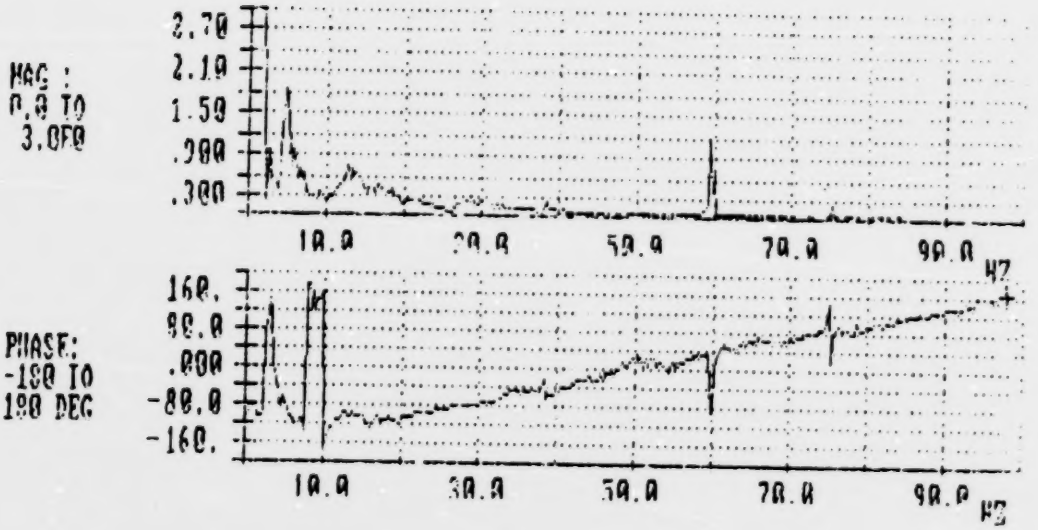


FIGURE 14

PREDICTED VELOCITY AT ELBOW FROM UPSTREAM MEASUREMENTS IN kPa, ASSUMING c = 275 m/s

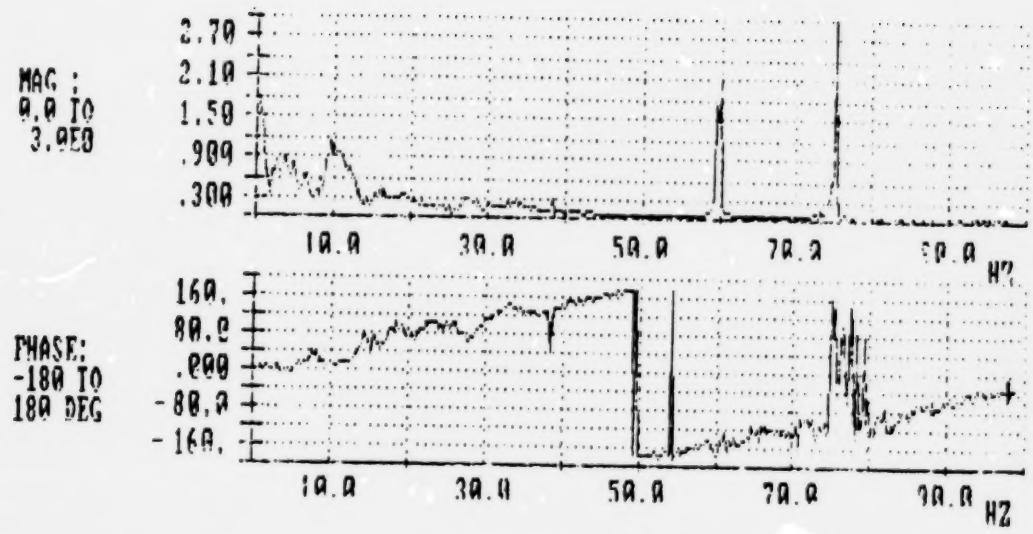


FIGURE 15

PREDICTED PRESSURE AT ELBOW FROM DOWNSTREAM MEASUREMENTS IN kPa, ASSUMING c = 275 m/s

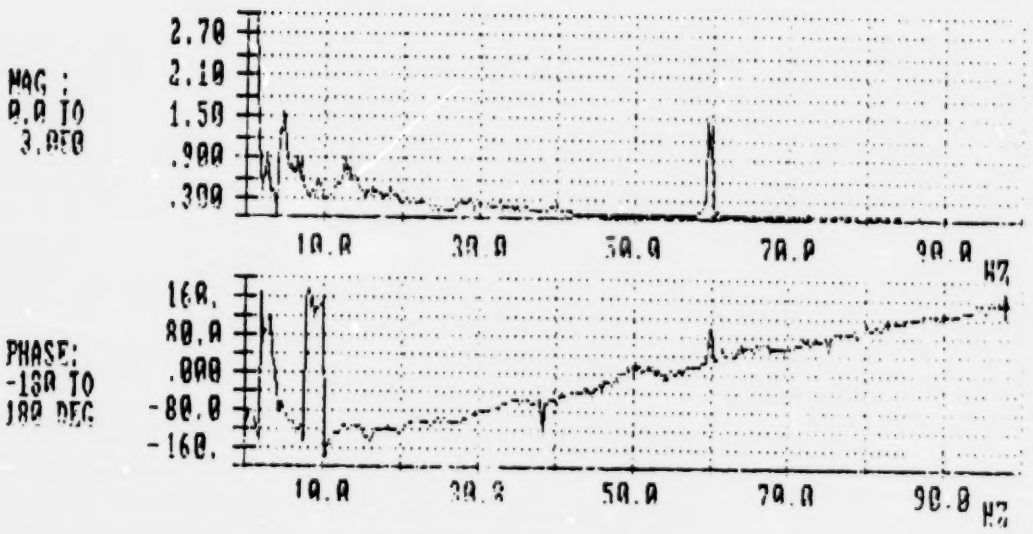


FIGURE 16

PREDICTED VELOCITY AT ELBOW FROM DOWNSTREAM MEASUREMENTS IN kPa, ASSUMING c = 275 m/s

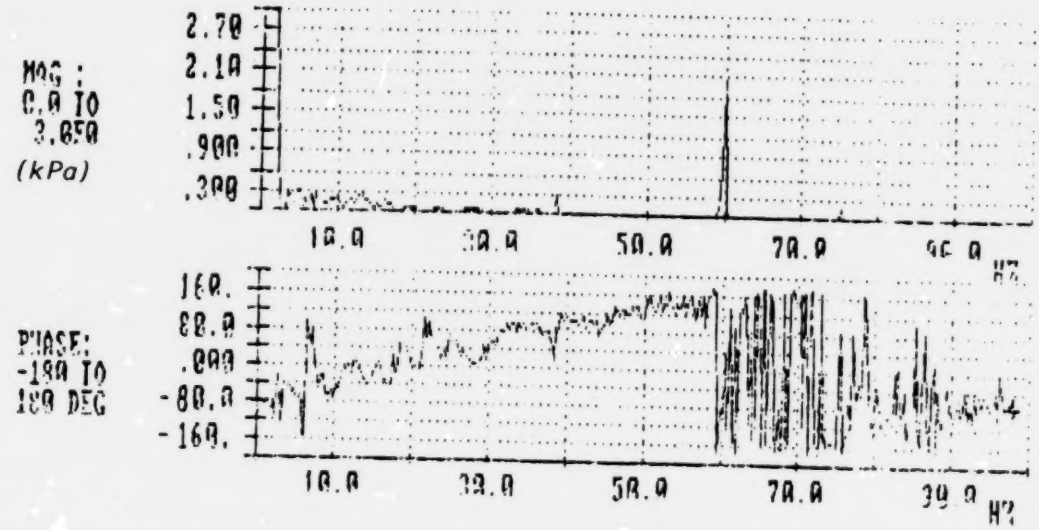


FIGURE 17

UPSTREAM VELOCITY MINUS DOWNSTREAM VELOCITY
IN kPa, ASSUMING c = 275 m/s

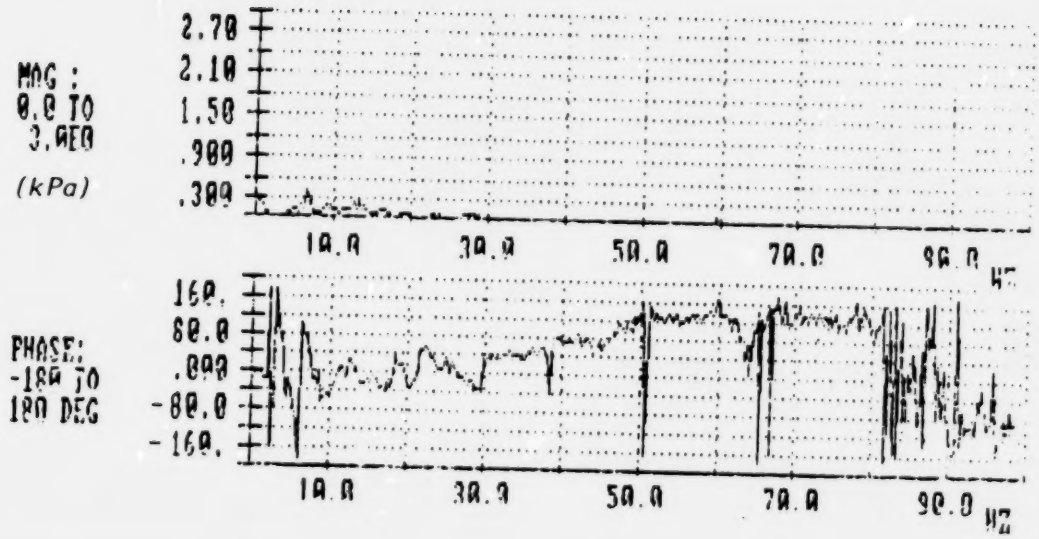


FIGURE 18

VELOCITY OF ELBOW IN kPa TIMES 1.4

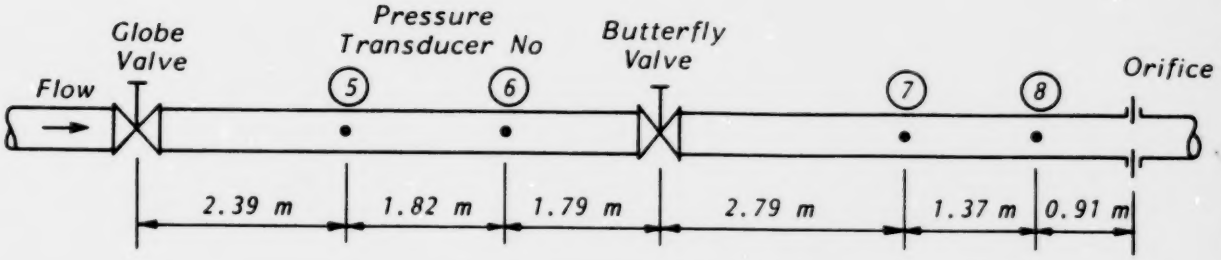


FIGURE 19
MEASUREMENTS AROUND A GLOBE VALVE
AND A BUTTERFLY VALVE

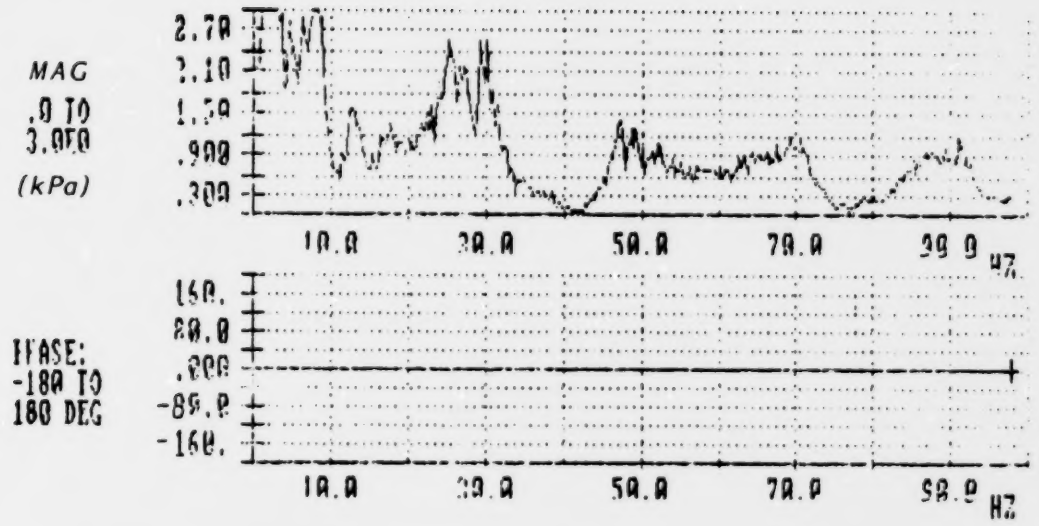


FIGURE 20
ACTUAL PRESSURE AT LOCATION 5

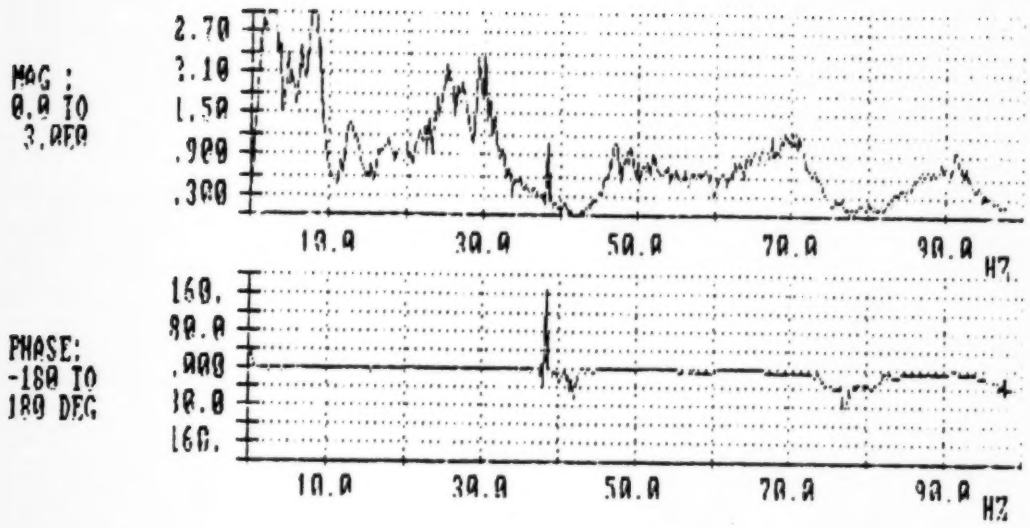


FIGURE 21

PREDICTED PRESSURE AT LOCATION 5 BASED ON DOWNSTREAM MEASUREMENTS

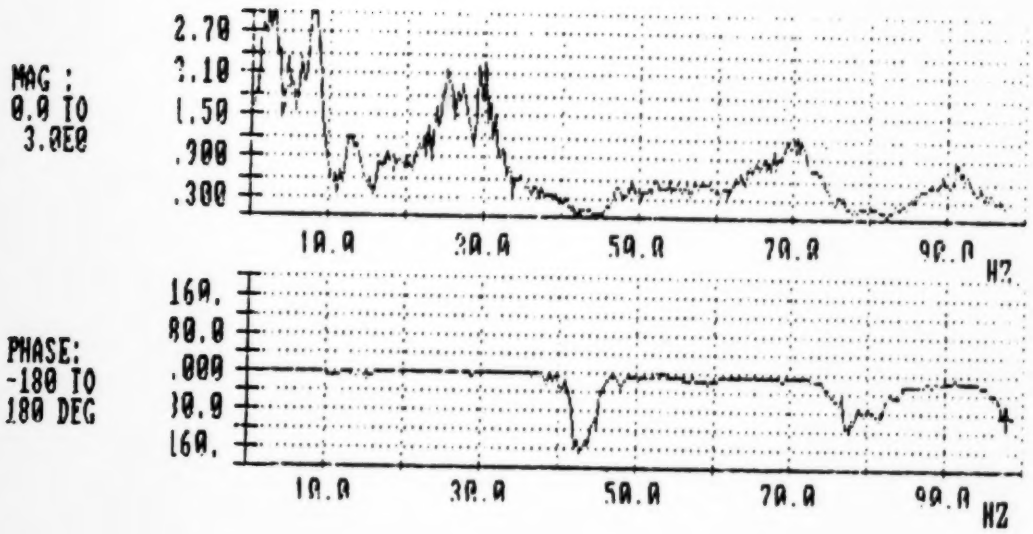


FIGURE 22

ACTUAL PRESSURE AT LOCATION 6

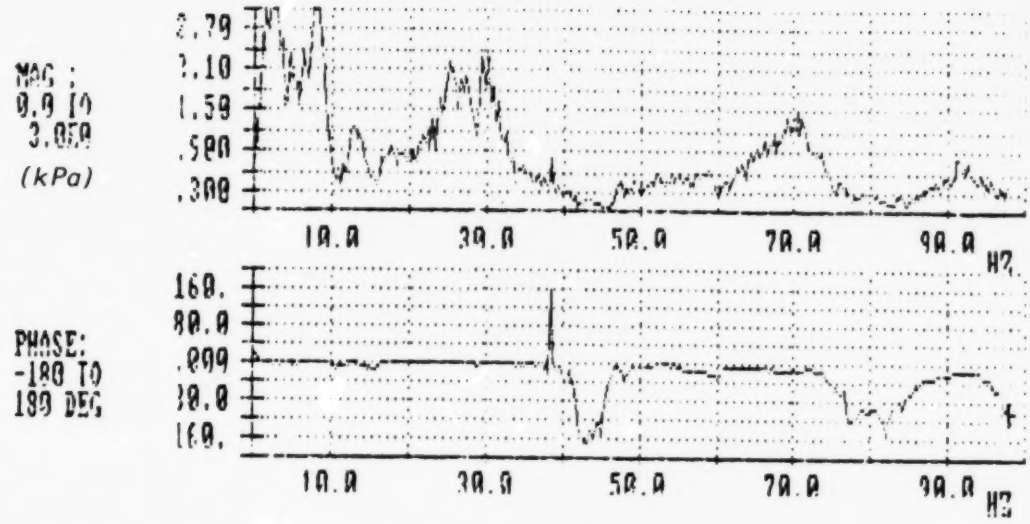


FIGURE 23

PREDICTED PRESSURE AT LOCATION 6 BASED ON DOWNSTREAM MEASUREMENTS

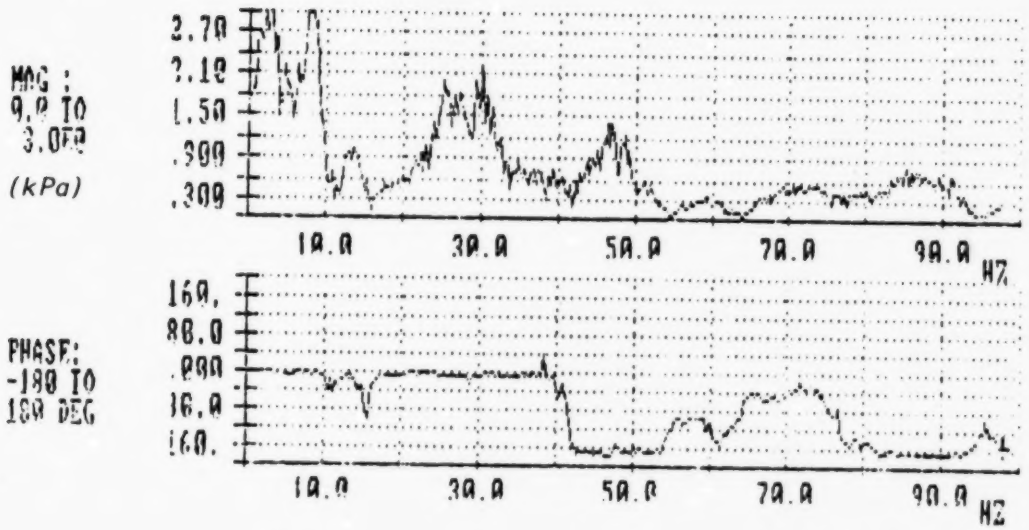


FIGURE 24

ACTUAL PRESSURE AT LOCATION 7

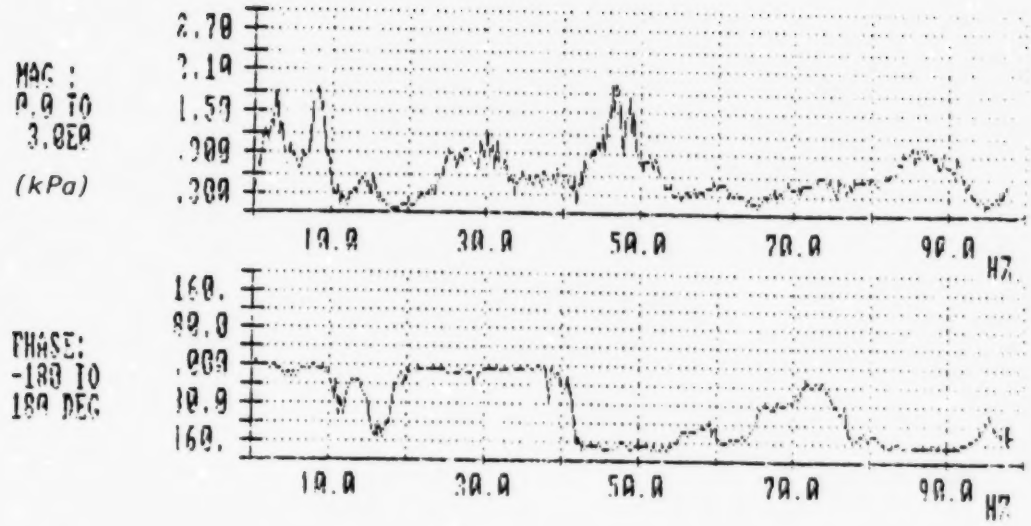


FIGURE 25

PREDICTED PRESSURE AT LOCATION 7 BASED ON UPSTREAM MEASUREMENTS

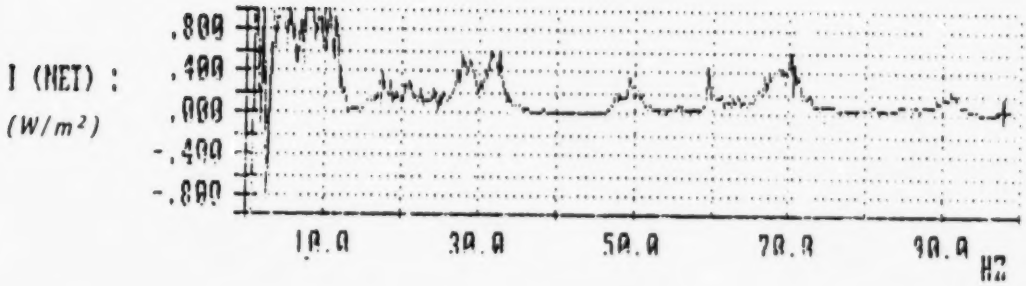


FIGURE 26

ACOUSTIC INTENSITY UPSTREAM OF BUTTERFLY VALVE, .9 SETTING

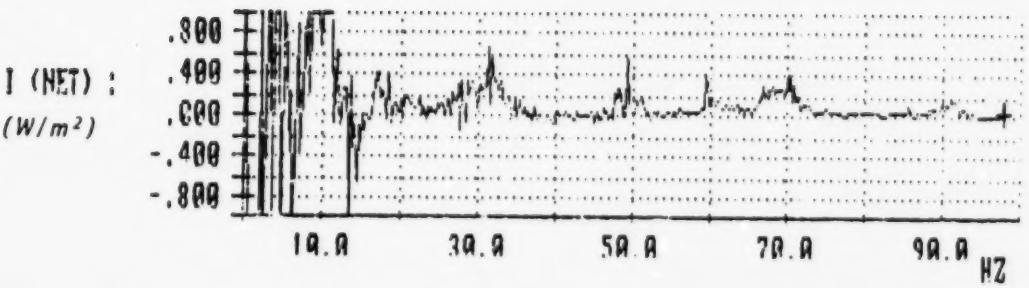


FIGURE 27

ACOUSTIC INTENSITY DOWNSTREAM OF BUTTERFLY VALVE, .9 SETTING

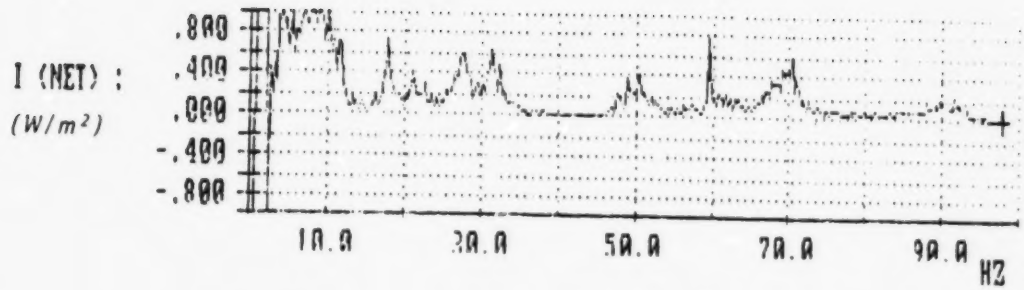


FIGURE 28

ACOUSTIC INTENSITY UPSTREAM OF
BUTTERFLY VALVE, .4 SETTING

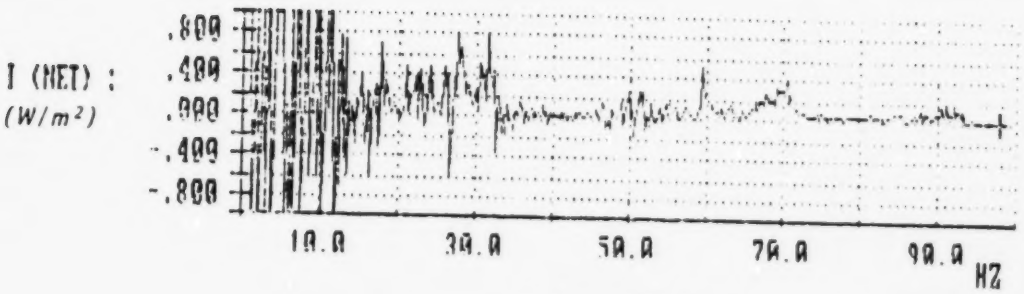


FIGURE 29

ACOUSTIC INTENSITY DOWNSTREAM OF
BUTTERFLY VALVE, .4 SETTING

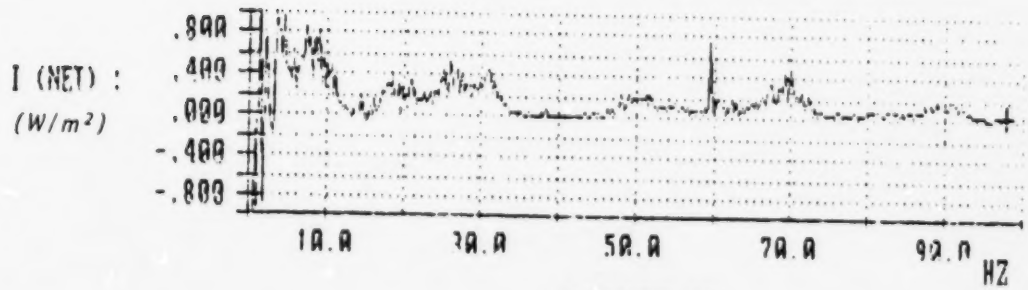


FIGURE 30

ACOUSTIC INTENSITY UPSTREAM OF
BUTTERFLY VALVE, .3 SETTING

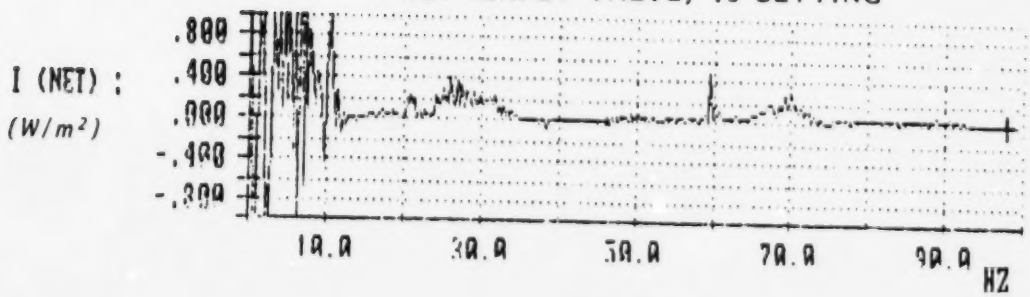


FIGURE 31

ACOUSTIC INTENSITY DOWNSTREAM OF
BUTTERFLY VALVE, .3 SETTING

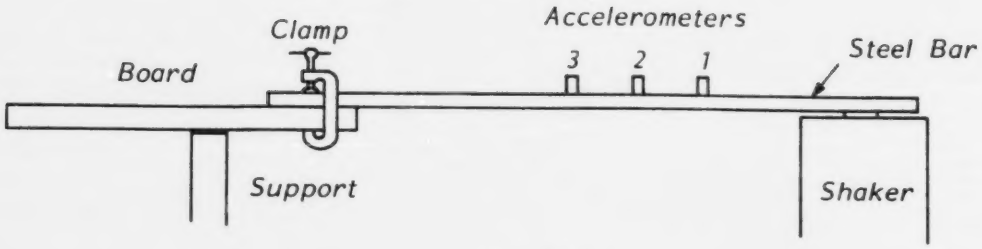


FIGURE 32
SET-UP FOR MEASUREMENT OF
STRUCTURAL WAVE INTENSITY

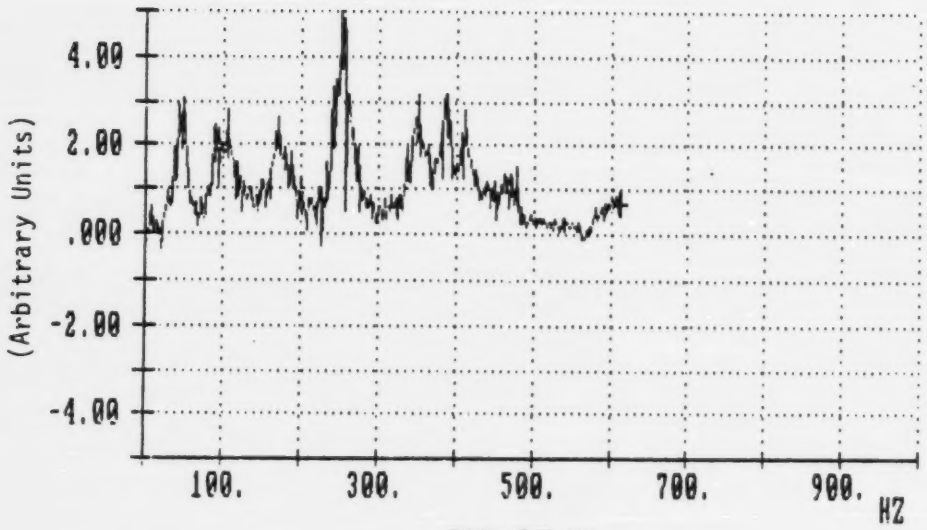


FIGURE 33
STRUCTURAL WAVE INTENSITY
FROM ACCELEROMETERS 1 AND 2

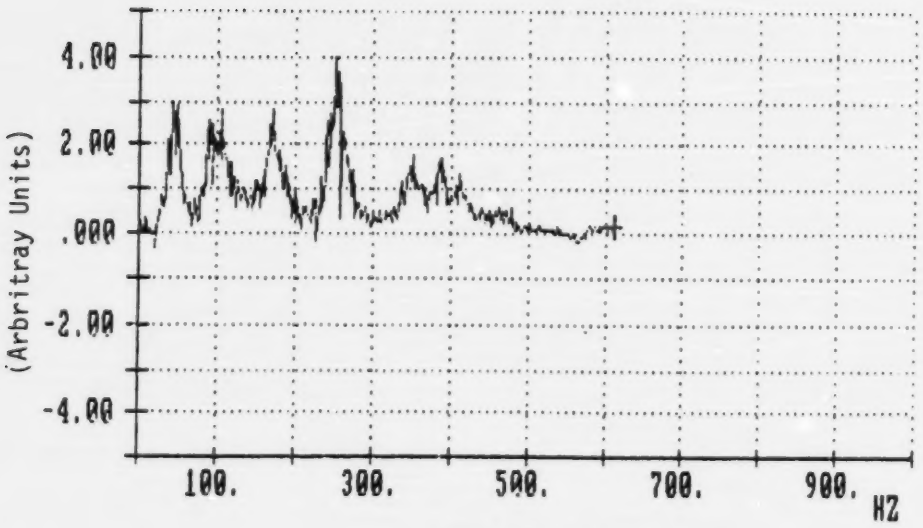


FIGURE 34
STRUCTURAL WAVE INTENSITY
FROM ACCELEROMETERS 1 AND 3

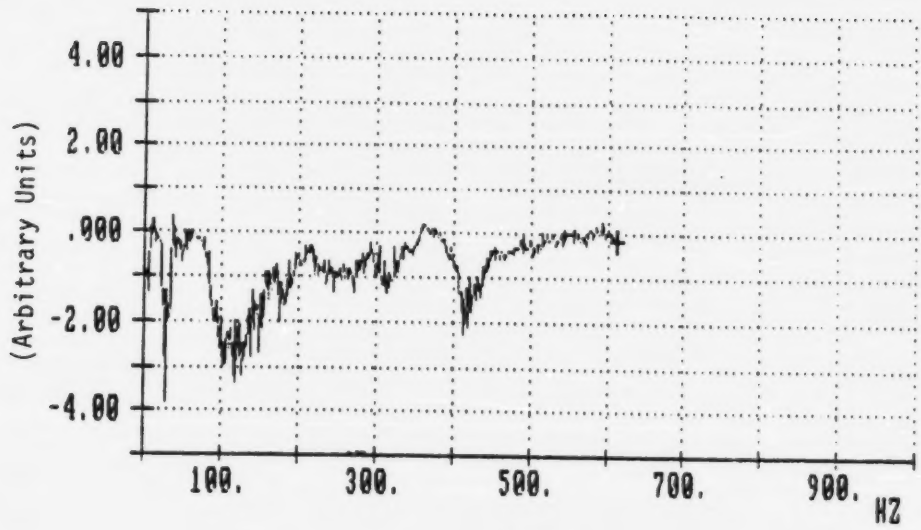


FIGURE 35

STRUCTURAL WAVE INTENSITY FROM ACCELEROMETERS 1 AND 2, WITH ENDS OF STEEL BAR REVERSED

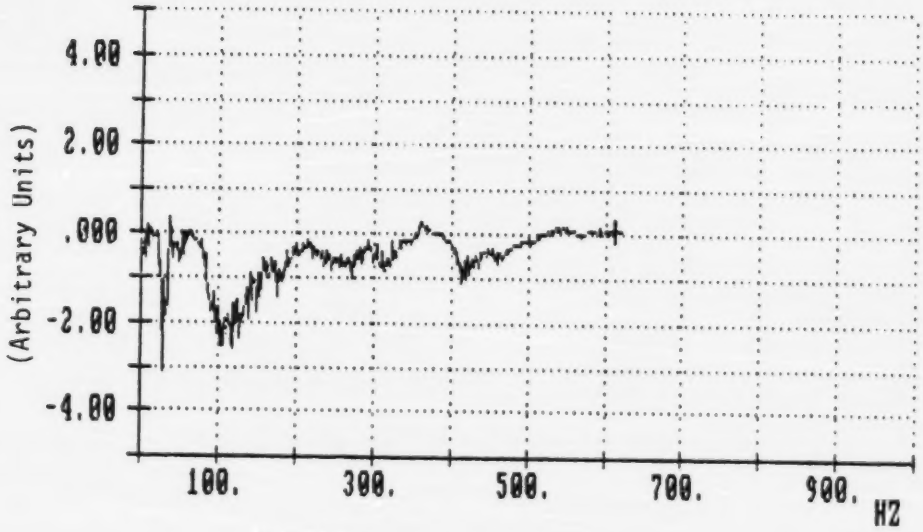


FIGURE 36

STRUCTURAL WAVE INTENSITY FROM ACCELEROMETERS 1 AND 3, WITH ENDS OF STEEL BAR REVERSED

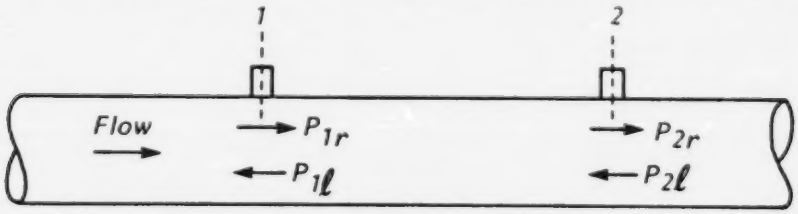


FIGURE 37

PRESSURE WAVES AT TWO MEASUREMENT LOCATIONS

APPENDIX A

FORMULATION FOR ACOUSTIC MEASUREMENTS

The acoustic intensity is calculated based on the signals from a pair of pressure transducers located at 1 and 2 along a pipe as shown in Figure 37. Pressure waves, simultaneously propagating in both left and right directions at both locations, are denoted by the subscripts 1, 2, ℓ and r. The basic conditions for valid measurements are plane-wave propagation in a uniform isotropic flow, absence of acoustic sources between the transducers and the signals being stationary random. In practice these conditions are approximately satisfied. Although the formulation is not restricted by finite difference approximation, it is desirable to keep the spacing between transducers to a minimum and to avoid taking measurements close to upstream flow disturbances. The following relations are based on Reference 3:

Reflection Coefficient at location 1:

$$R1 = (H12 - H\ell) / (Hr - H12)$$

where
- $H12 = S12/S11$
  - = acoustic transfer function
- $S12$ = cross-spectral density between the two transducer signals
- $S11$ = autospectral density of the signal at location 1
- $H\ell = \exp(-j(ks/(1+M)))$
- $Hr = \exp(j(ks/(1-M)))$
- j = imaginary unit
- k = wave number = w/c
- w = angular frequency
- c = sound speed
- M = Mach number = Mean flow speed/c

Acoustic intensity for uniform flow:

- I = net intensity
  - = $Ir - I\ell$
- Ir = right-running intensity
  - = $(1 + M)^2 (Srr/(\rho c))$
- $I\ell$ = left-running intensity
  - $(1 - M)^2 (S\ell\ell/(\rho c))$
- $Srr = S11 / |1 + R1|^2$
- $S\ell\ell = S11 / |1 + 1 / R1|^2$
- $S11$ = autospectral density at location 1
- ρ = mean fluid density

APPENDIX B

FORMULATION FOR STRUCTURAL WAVE INTENSITY

The formula for structural wave intensity is based on the assumption that the spacing between two accelerometers is small compared with the wavelength. It is therefore necessary to estimate the minimum wavelength based on the maximum frequency before calculating the intensity.

(A) Calculation of Wavelength

For a bar or plate with a uniform section, modulus of elasticity Y, density ρ, radius of gyration k (= t/$\sqrt{12}$ for a bar of thickness t and a/2 for a rod of radius a), and at an angular frequency w, the speed of propagation of bending waves is given by

$$v = \sqrt{w\ c\ k}$$

where $c = \sqrt{Y/\rho}$

The wavelength is $2\pi\ v\ /\ w$. Two examples are given below.

1) 17.7 mm Thick Steel Bar

As an example, for a steel plate of 17.7 mm thickness and a frequency of 100 Hz, c = 5127 m/s, v = 108.7 m/s, and wavelength = 1.09 m. At 600 Hz, the wavelength is .44 m. In order to measure the bending waves on the bar up to a certain frequency, the spacing between accelerometers has to be less than, say, 1/10 the wavelength at that frequency. In the test described in Section 4.4 the spacing between accelerometers is .038 m. Thus the intensity calculated from the signals of adjacent accelerometers is expected to be reasonably accurate up to 600 Hz. The intensity calculated from the signals from accelerometers 1 and 3 (the spacing is doubled) is valid up to 1/4 of 600, or 150 Hz.

2) 16", Sch 30 Steel Pipe

From tables in a mechanical handbook, the radius of gyration of the pipe section is .14 m. The wave speed for an empty pipe at 10 Hz is

$$v = \sqrt{10 \times 2\ \pi \times 5127 \times 0.14} = 212.7 \text{ m/s}$$

giving a wavelength of 21.3 m. At 100 Hz, the wavelength is 6.74 m. When the pipe is full of water, it is assumed that the water only increases the effective density of the pipe material and does not contribute to the bending stiffness of the section. With this assumption, c changes to 3407 m/s, and the wavelength changes to 17.3 m at 10 Hz and 5.5 m at 100 Hz.

B) Bending Wave Intensity

The bending wave intensity along a uniform beam, based on Reference 4, is in the form

$$I = -2 \sqrt{B\,m}\,/(w^2\,d)\ \mathrm{Im}\,[S12]$$

where the intensity I is in the direction from accelerometer 1 to 2, B is the bending stiffness, m is the mass per unit length, d is the distance between accelerometers and Im [S12] is the imaginary part of the cross spectrum between the acceleration signals. It is noted that if the signals are in velocity (obtained by analog integration), then w^2 in the denominator must be omitted. The above formula applies to plates as well as pipes.

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